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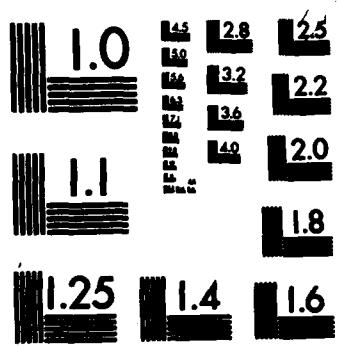
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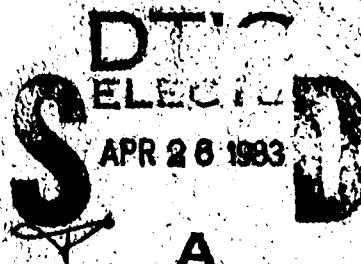
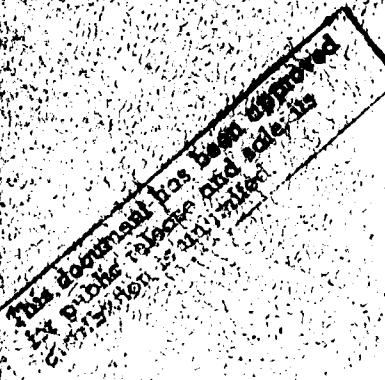
RECENT DEVELOPMENT OF
HIGH-POWER VISIBLE LASER
SOURCES EMPLOYING SOLID-STATE
SLAB LASERS AND NONLINEAR
HARMONIC CONVERSION TECHNIQUES

by

Y.S. Liu, W.B. Jones, and J.P. Chernoch

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SUMMARY	Recent developments in high-power solid-state lasers (Nd:YAG, Nd:glass) have greatly improved both average power capability and beam brightness. This has been a result, to a large extent, of the development of the total-internal-reflection slab-type solid-state laser configuration, which provides a self-compensating mechanism to minimize the thermally induced distortion commonly observed in solid-state lasers. ^(1,2,3) Near diffraction-limited, high peak power, high average power solid-state lasers are ideal pump sources for nonlinear frequency conversions using harmonic generation, stimulated Raman scattering and/or pumping dye lasers for ultraviolet (UV), visible, and infrared (IR) coherent light sources. Continuously tunable coherent sources covering a spectral range from 0.2 μm to beyond 3 μm , using these combined techniques, have been reported. ⁽⁴⁾			NO. PAGES	8
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RECENT DEVELOPMENT OF HIGH-POWER VISIBLE LASER SOURCES EMPLOYING SOLID-STATE SLAB LASERS AND NONLINEAR HARMONIC CONVERSION TECHNIQUES

Y.S. Liu, W.B. Jones, and J.P. Chernoch

INTRODUCTION

A slab-type solid-state laser which produces a high-brightness laser beam at high pump powers has been developed. The configuration is particularly useful for glass host material operated at high average power levels. Although laser glass is available in large volumes of good optical quality and glass lasers can produce high-energy pulses over a wide range of pulse durations, the use of the glass laser in the standard rod configuration has been limited in average power capability because the relatively low heat conductivity of glass leads to high thermal stress at high pump power and, thus, large optical distortion.

In the slab-type laser configuration, the solid host material (e.g., Nd:glass, Nd:YAG) is in the form of a rectangular cross-section slab with plane parallel surfaces or faces. The configuration is shown schematically in Figure 1a. The slab is face-pumped optically, i.e., illuminated through two opposing slab faces, to obtain the required inversion energy in the active material, and, simultaneously, the same faces are cooled to obtain a one-dimensional, steady, thermal state. Thermal stress results in the slab from the heating which is concomitant with optical pumping and cooling. The volume heating is symmetrical relative to the center plane of the slab, and, therefore, the thermal stress averaged from one slab surface to the other is zero. These conditions lead to a high degree of compensation for thermal-optic distortion for a beam passing from one slab face to the other. The laser beam is introduced into the slab through suitable entrance optics, usually through a surface at Brewster's angle, as shown in Figure 1b. With this arrangement, a relatively thin slab of solid host material can be used so that efficient cooling is possible, and at the same time, the active material is swept efficiently by the beam.

Near diffraction-limited, high peak power, and high average power solid-state slab lasers are ideal pump sources for nonlinear frequency conversion, using harmonic generation and stimulated Raman scattering for generating visible, UV, and IR coherent sources. The advances in this type of

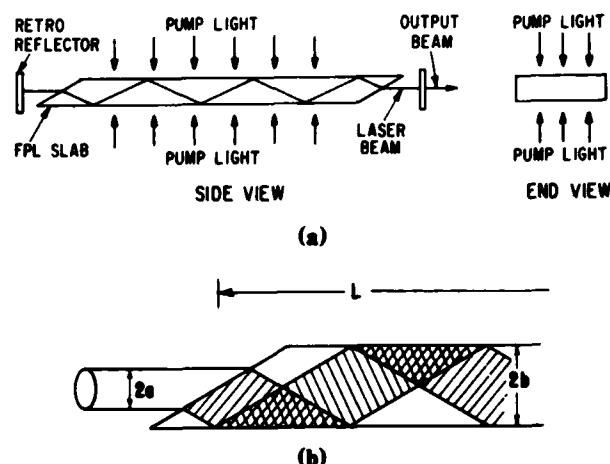


Figure 1. (a) Schematic of a total-internal-reflective slab laser. (b) Brewster-angle entrance face of a slab laser.

solid-state pump laser have led to the progress made in the development of high-power visible laser sources using harmonic conversion techniques. In this report, we review the recent development in solid-state slab lasers (Nd:glass, Nd:YAG) and discuss parameters relevant to the high-power second harmonic generation using nonlinear crystals. These discussions are applicable to other types of harmonic conversions, such as third and fourth harmonic generation.

SOLID-STATE SLAB-TYPE LASERS

The cross section of an arrangement of a slab laser, pump lamps, and lamp reflectors is shown in Figure 2. The intrinsic compensation for thermal-distortion effects occurs only for paraxial rays in a plane of reflection (p -plane). In the ideal case, the thermal gradients are parallel to a p -plane and, therefore, the principal thermal-optic distortion in the slab is compensated intrinsically. However, if the inversion pumping (strictly slab heating) is not uniform across the slab width, transverse thermal gradients will occur for which there is no intrinsic compensation. Consequently, care must be taken that the pumping distribution is uniform across the slab width to avoid distortion perpendicular to the

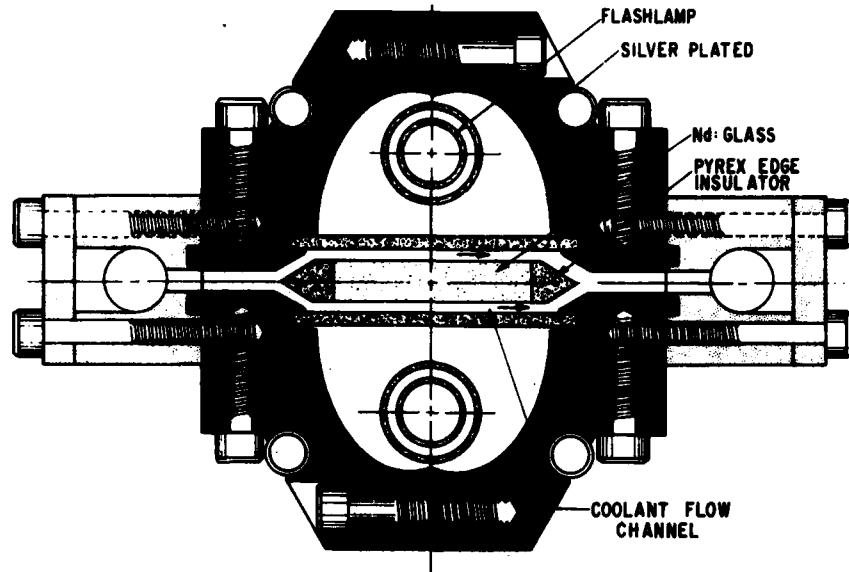


Figure 2. Cross section of a slab laser enclosure showing arrangement of slab, pump lamps, and lamp reflectors.

p-plane. In practice, this has entailed a careful design of the reflectors for the pump lamps in order to achieve the required uniformity of pumping, as well as efficient coupling between the discharge lamps and the active material.

Slab cooling must be arranged so that the faces are cooled to equal temperatures and temperature gradients along the slab faces are minimized. In practice slab cooling has been accomplished either by convection cooling with a fluid (of sufficiently small refractive index) flowing across the slab faces or by conduction cooling through a thin layer of gas to the cooled windows used for the pump radiation. In either case the problem of minimizing surface temperature gradients occurs mainly at the lateral edges where the slab supports are located.

The slab configurations have been operated in a variety of modes for a number of applications. In all designs that have been implemented, the pump lamps employed have been linear discharge tubes Kr-filled for continuous wave (cw) operation and Xe-filled for pulsed operation. Two types of solid host materials have been used: Nd:YAG and Nd:glass. Nd:YAG is a crystalline material with relatively high heat conductivity available only in limited sizes of good optical quality. For these reasons, slab fracture due to thermal stress is of no concern in YAG designs, for pumping is limited by pump-lamp characteristics much below rates for which the slab heating can cause thermal fracture. Single-slab Nd:YAG laser designs have operated cw at 150 W beam power output, pulsed mode at 5 J/pulse, 20 pps, and Q-switched at 0.5 J/pulse,

20 pps, all with beam quality less than five times diffraction-limited. Designs with Nd:YAG have also been used as low-distortion amplifiers for Q-switched oscillators at repetition rates up to 20 pps.

In contrast to Nd:YAG, Nd:glass is available in essentially any desired size, with excellent optical quality. The low specific-gain coefficient of glass makes it useful only for pulse-pumped operation. The low heat conductivity is the key factor that sets a limit on glass slab thickness that can be used in a given design without exceeding the thermal fracture limit. In typical designs for operation in the range 3 to 10 pps, the inversion that can be obtained, which is compatible with useful pump-lamp operation, falls in the range 0.25 to 0.5 J/cm³ per pump pulse. For 10 pps operation, the heating associated with the desired inversion per pulse limits the slab thickness to approximately 6 mm. Since the thermal stress in a slab is proportional to the thickness squared for a given heat loading density, 12 mm is a suitable thickness for 3 pps operation.

The principal application of the Nd:glass slab laser has been as a Q-switched oscillator-amplifier in a single slab operating at a repetition rate of 3 to 10 pps, with an output beam energy greater than 2 J/pulse and of sufficiently good quality for efficient second harmonic generation in a KD*P crystal. Unlike the traditional rod geometry, the slab laser with its large aperture aspect ratio lends itself to incorporation of both functions, oscillator and amplifier, in a single laser head. This provides a higher overall efficiency with a reduction in system complexity. Although the thermal self-

compensating aspects of the slab geometry and the low gain necessary for the specific performance would permit the operation of an oscillator at high average powers, other system components, such as the Pockels cell and cavity mirrors, are more limited in average power thermal capability and rule out use of a single multipass oscillator. Furthermore, efficient second harmonic generation using KD*P (Type II), requires power densities on the order of 100 to 150 MW/cm² with a beam divergence of less than 1 mrad. This requirement dictates TEM₀₀ mode operation for the oscillator. In an oscillator-amplifier configuration, TEM₀₀ mode operation is more easily maintained. In general, at the beam energy levels of interest here, the folded-beam amplifier is required in order to obtain sufficient beam intensity.

The limit on beam quality obtainable with the Nd:glass slab laser is determined by the spurious temperature gradients that result from nonuniformities in pumping and cooling of the slab. The low thermal conductivity of glass causes thermal gradients, and thus thermal distortion, to be very sensitive to nonuniformities in heating and cooling. In all practical cases, there is significant thermal distortion in the *s*-plane with maximum pumping power, but the intrinsic compensation in the *p*-plane results in negligible distortion in this plane.

In one laser design, a 6-mm thick, 46-mm wide, 280-mm long slab of LHG-5 phosphate glass is employed. The slab is pumped with two 10-mm bore, 20-cm long, Xe-filled flashlamps in the arrangement shown in Figure 2. The slab is convection-cooled by flowing an ethylene glycol and water mixture over the polished slab faces. Figure 3 shows the distortion measured with a shearing interferometer and plotted as the deflection (in the *s*-plane) of a ray passing through the slab at positions along the width of the slab. This distortion results from pumping at the maximum permissible power level (which produces 0.28 J/cm³ inversion, 10 pps). The central 10 mm of aperture width has very low distortion, and for a total aperture width of 33 mm the distortion is sufficiently low for a high-quality amplifier. Near the lateral edges of the slab aperture, the distortion increases due to the large temperature gradients near the edges. The laser oscillator-amplifier is configured with an electro-optic, *Q*-switched oscillator with one beam pass through the slab in a central part of the aperture area where the lowest distortion is measured. The oscillator produces a TEM₀₀ beam of 0.25 J/pulse. The remainder of the slab is used in a four-pass folded amplifier to yield a beam of 2 J/pulse. The beam suffers some distortion in the four-pass

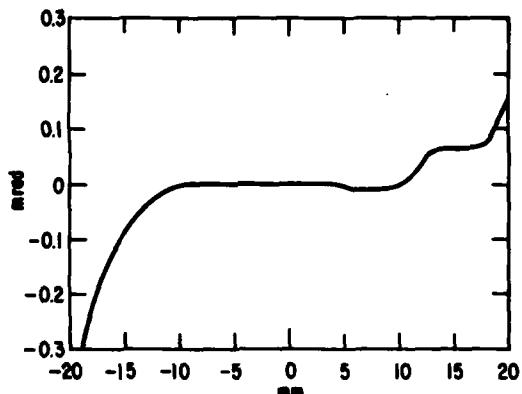


Figure 3. Thermal distortion measured as a probe ray deflection vs position in the Nd:glass slab aperture.

amplifier and emerges with a divergence of approximately three times the diffraction limit. The beam quality at this energy level is adequate for efficient (40%) second harmonic conversion in a Type II KD*P crystal.

HIGH-POWER NONLINEAR HARMONIC CONVERSION

In this section, techniques and design parameters for generating high average power visible radiation using harmonic conversion from a slab-type solid-state laser are discussed. Although the second, third, and fourth harmonic generation from a Nd solid-state laser, using various nonlinear crystals, has been well studied, efficient second harmonic conversion from a solid-state slab-laser in the average power range, exceeding 10 W and pulse energy over several joules, imposes some severe constraints with respects to both the fundamental beam properties (such as beam brightness, pulse shape, and transverse mode distribution) and the nonlinear media employed.

Phase Matching Properties

It is well known that efficient second harmonic generation in nonlinear crystals requires phase matching of the fundamental and second harmonic wave vectors. Dispersion and double refraction characteristics of a crystal determine its phase matching properties. The second harmonic conversion efficiency can be expressed as,

$$\eta = \eta_0 \text{sinc}(\Delta k \cdot L/2) = \eta_0 \text{sinc} \phi, \quad (1)$$

where η_0 is the power conversion efficiency under the perfect phase-match condition and η_0 is a function of the incident power density and the effective nonlinear coefficient of the crystal. Further,

$$\Delta k = k_2 - 2k_1,$$

with $k_1 = 2\pi n_1/\lambda$, and $k_2 = 2\pi n_2/\lambda_2$,

where n_1 , n_2 , λ_1 , and λ_2 denote the refractive indices and the wavelengths for the fundamental and second harmonic waves, respectively. The function $\text{sinc}\phi = (\sin\phi/\phi)^2$ is the phase mismatch term, where $\phi = \Delta k \cdot L/2$ and L is the interaction length for the fundamental and second harmonic waves in the crystal.

The maximum conversion efficiency is obtained when $\phi = 0$, i.e., with no phase-mismatch. The quantity ϕ is a function of many parameters, and $\delta\phi$ can be expressed as

$$\begin{aligned} \delta\phi = & \frac{\partial\phi}{\partial\lambda}\delta\lambda + \frac{\partial\phi}{\partial\theta}\delta\theta + \frac{\partial\phi}{\partial T}\delta T \\ & + \frac{\partial\phi}{\partial E}\delta E + \dots, \end{aligned} \quad (2)$$

where $\delta\lambda$, $\delta\theta$, δT , and δE denote the deviations with the wavelength, angular displacement, temperature, and the applied electric field from the perfect phase-matching condition. For high-power applications, these quantities are interrelated and the maximum conversion efficiency is realized when the sum of the terms in Equation 2 is minimized.

The spectral phase-matching properties of several commonly used nonlinear crystals have been measured; the results are shown in Figure 4.^(5,6) In these measurements, the relative second harmonic conversion efficiency vs wavelength was measured using a line-narrowed, tunable Nd:glass laser, and scanning across its

bandwidth. The spectral phase-matching conditions have been measured for the following materials:

1. LiNbO₃, 90° phase-matched, temperature-tuned,
2. Deuterated CsH₂AsO₄ (CD*^A), 90° phase-matched, temperature-tuned,
3. LiIO₃, Type I angle-tuned at 22 °C,
4. KH₂PO₄ (KDP), Type I angle-tuned at 22 °C,
5. Deuterated KH₂PO₄ (KD*^P), Type II angle-tuned at 22 °C, and
6. KTiOPO₄ (KTP), Type II angle-tuned at 22 °C.

The phase-matching bandwidth is defined as $L \cdot \Delta\lambda$, where $\Delta\lambda$ is the full-spectral width of the fundamental wavelength at which the second harmonic conversion efficiency is reduced to one-half the maximum value (FWHM).

The spectral phase-matching bandwidth is of concern when a wideband source, such as a Nd:glass laser, is employed. The typical spectral bandwidth of a Q-switched Nd:glass oscillator is about 100 Å. Thus line narrowing is required in a Nd:glass laser for high-efficiency second harmonic conversion.

Among various tuning techniques, we have found that an intracavity Brewster-angle birefringent filter offers a simple and lossless tuning method particularly useful for a low-gain, high-power oscillator, such as a Nd:glass laser.⁽⁷⁾ Birefringent materials, such as LiNbO₃, can be used for low-power applications, while materials with a higher damage threshold, such as KDP and quartz,

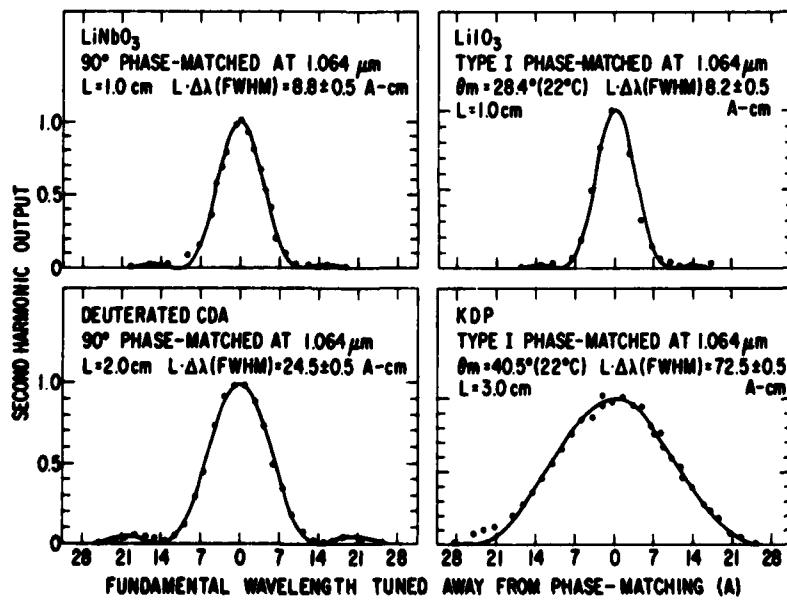


Figure 4. Spectral phase-matching characteristics in various nonlinear crystals at 1.06 μm .

are required for high-power applications. The tuning and line-narrowing characteristics for a Q-switched Nd:glass oscillator, using an x-cut LiNbO₃ birefringent filter, are shown in Figure 5. For the higher power application, a 3-mm thick KD*P has been employed at an intracavity power density exceeding 500 MW/cm² without damage. However, additional low-finesse solid etalons are required to reduce the line width to about 1 Å.

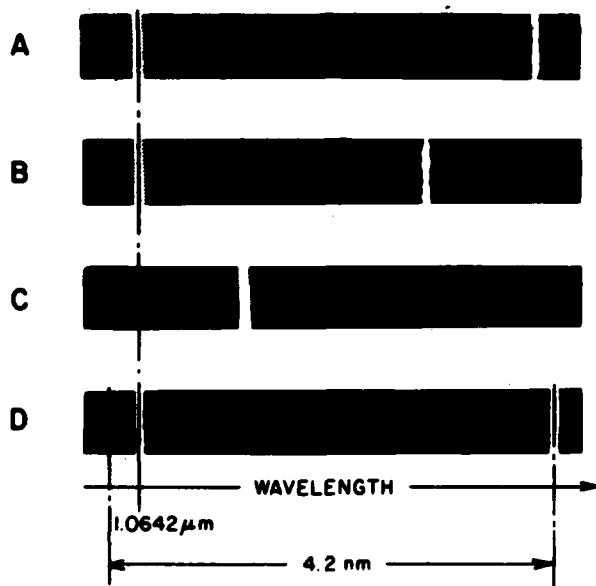


Figure 5. Spectral output of a line-narrowed Q-switched Nd:glass oscillator using a LiNbO₃ birefringent plate.

From measurements of the relative second harmonic conversion efficiency vs angle and vs crystal temperature, bandwidths for these parameters can be assigned to each crystal in a manner similar to the spectral phase-matching bandwidth. These and other properties for several materials useful for high average power second harmonic generation are summarized in Table 1. The angular bandwidth is important in determining requirements for the fundamental beam quality to achieve efficient second harmonic conversion. The temperature bandwidth is indicative of the required crystal temperature control for efficient second harmonic conversion and also indicative of the tolerance of a crystal for temperature gradients resulting from beam power absorption.

Nonlinear Materials with High-Power Capability

The selection of a nonlinear optical material for application at an average power exceeding 10 W is limited by the average power and peak power densities that a crystal can tolerate. Thermally induced

phase mismatch, resulting from beam power absorption, limits the average power capability. The damage threshold limits the peak power density capability. There are only a few optical crystals available that satisfy these requirements. These are: KD*P, CD*A, and the most recently developed KTP crystals. Each of these crystals has properties which are unique for certain applications. Table 2 lists some of the special characteristics of these crystals. Some of the unique properties of these crystals and the results obtained with them are reviewed below.

KD*P (Deuterated KH₂PO₄). KD*P is the most highly developed of the three nonlinear crystals discussed. The deuterated material is required to reduce absorption at 1.06 μm and thus minimize the thermally induced phase mismatch. Crystals are available in large sizes with excellent optical quality.

The KD*P crystal has a low absorption constant ($< 0.01 \text{ cm}^{-1}$) and a high power-density damage threshold at 1.06 μm. Effects due to thermally induced phase mismatching are negligibly small at an incident average power level up to about 25 W, with peak power density of 250 MW/cm² and a 35 ns pulse duration. Nonlinear absorption due to two-photon processes is also insignificant under these conditions.

The effective nonlinear constant of a KD*P crystal depends upon the types of nonlinear interactions involved. It can be shown that the effective nonlinear constant for the Type II interaction, relative to that for Type I, is proportional to $(\sin 2\theta_{II})/(\sin \theta_I)$, where θ_I and θ_{II} are, respectively, the phase-matching angles for each type of phase matching. Given that $\theta_I = 41.5^\circ$ and $\theta_{II} = 53.5^\circ$, the ratio has a value of 1.44, and, consequently, enhancement of the second harmonic efficiency by a factor of about two can be obtained by using the Type II phase matching instead of the Type I.

A critical parameter in achieving a high conversion efficiency is the angular tolerance for phase matching. This is particularly important in the high-power application because of the difficulty in maintaining a low divergent beam. The angular tolerance for phase matching in Type II interaction for KD*P is greater by a factor of about two, as compared to that found in the Type I. The values of $L\Delta\theta$ were measured to be 5 mrad-cm for a KD*P (Type II) and 2.4 mrad-cm for KD*P in Type I interaction.

In Figure 6, the energy conversion efficiency as a function of the incident power density is shown for a KD*P crystal of 35-mm length.

Table 1
**SUMMARY OF PHASE-MATCHING
PROPERTIES FOR SECOND HARMONIC
GENERATION IN KD*P, CD*A, AND KTP**

Type of Phase Matching and Temperature	KD*P		CD*A		KTP
	Type I @ 22 °C	Type II @ 22 °C	Type I @ 22 °C	90° @ 105 °C	Type II @ 25 °C
Spectral Bandwidth $L \cdot \Delta\lambda$ (FWHM) (Å-cm)	72.5	55.7	22.5	22.5	5.7
Angular Bandwidth $L \cdot \Delta\theta$ (FWHM) (mrad-cm)	2.4	5	9	> 50	15
Temperature Bandwidth $L \cdot \Delta T$ (FWHM) (°C-cm)	6†	6.	6†	6	15
Phase-matching angle @ 1.06 μm	41°	53.5°	82°	90°	26°
Walk-off angle (mrad)	27	18	3.1	0	1

† Values are estimated

Table 2
**PROPERTIES OF KD*P, CD*A, AND KTP
FOR DIFFERENT TYPES
OF PHASE-MATCH AT 1.06 μm**

Crystal	Type of Phase Matching	Properties
KD*P	Type II @ 22 °C	<ul style="list-style-type: none"> • Effective nonlinear coefficient larger than Type I • Angular bandwidth larger than Type I • Large spectral bandwidth • High damage thresholds for both peak power and average power • Sensitive to temperature change • Larger-size material available
CD*A	90° @ 105 °C	<ul style="list-style-type: none"> • Noncritical phase match • Higher efficiency than that of KD*P • Lower damage threshold • Dehydration at ~ 150 °C causing permanent damage • Larger size crystal not available
	Type I @ 25 °C	<ul style="list-style-type: none"> • Room-temperature Operation • Improved damage threshold
KTP	Type II @ 25 °C	<ul style="list-style-type: none"> • Large nonlinear coefficient • High conversion efficiency • Relatively insensitive to temperature variation • Small walk-off angle • Nonhygroscopic • Crystal size limit

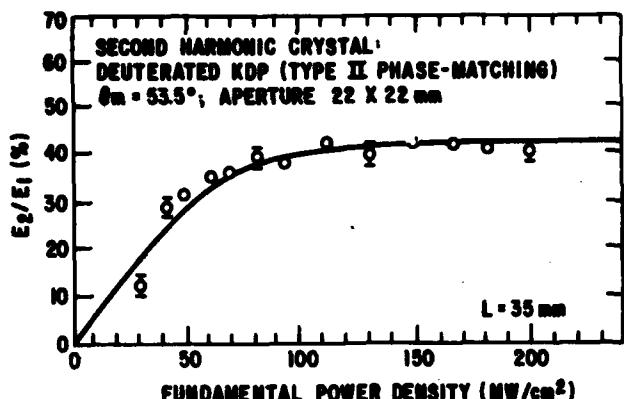


Figure 6. The energy conversion efficiency as a function of incident power density for a deuterated KDP.

CD*A (Deuterated CsH_2AsO_6). CD*A is iso-morphic with KD*P and is usually found to be a more efficient harmonic converter than KD*P. The temperature-tuned, 90° phase-matched CD*A is a preferred configuration. However, the 90° phase-matching temperature of the crystal at $1.06 \mu\text{m}$ is $\sim 110^\circ\text{C}$. This temperature is sufficiently high that the crystal is susceptible to damage due to dehydration, which occurs at about 150°C .⁽⁸⁾ The damage level for a temperature-tuned CD*A was less than 10 W at an energy density of about $2 \text{ J}\cdot\text{cm}^{-2}$ (35 ns). This property has severely limited the usefulness of 90° phase-matched CD*A for high-power harmonic conversion.

The CD*A can also be used in higher-power applications with Type I angle-tuned phase matching at room temperature. This configuration is illustrated in Figure 7. The upper graph shows the crystal orientation and the incident $1.06-\mu\text{m}$ beam polarization. The lower curve shows the angular phase-matching tolerance in θ -direction; a value $\Delta\theta L = 9.0 \text{ mrad}\cdot\text{cm}$ has been measured. The angular phase-matching tolerance in ϕ -direction has a value close to that of a 90° phase-matched crystal. Due to a larger angular tolerance, Type I CD*A is usually found to be more efficient in second harmonic generation than KD*P (Type II).

KTP (KTIOPO_4). KTP is a new type of nonlinear crystal which is currently under development.^(6,9) The crystal exhibits several unique properties, including a high nonlinear coefficient comparable to

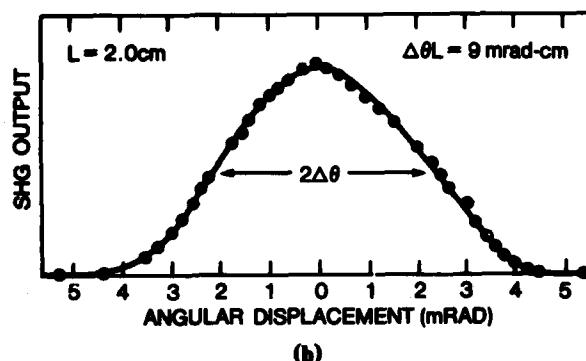
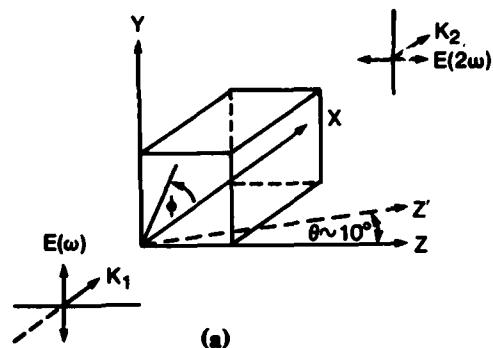


Figure 7. (a) CD*A crystal orientation in a Type I angle-tuned configuration. (b) Angular phase-match bandwidth in θ -direction for a Type I CD*A angle-tuned at room temperature.

that of $\text{Ba}_2\text{NaNb}_5\text{O}_{15}$, a high damage threshold, and a low degree of sensitivity to thermally induced phase mismatch. These combined properties make KTP the most attractive crystal for high-power frequency conversion.

The spectral, angular, and temperature phase-matching characteristics for second harmonic generation at $1.06 \mu\text{m}$ in KTP are shown in Table 1. The large temperature bandwidth observed is a unique characteristic of this nonlinear material. Because of its large nonlinear coefficient, this further reduces the length of crystal required for high conversion efficiency. As a result, a second harmonic generation efficiency near 50% can be readily obtained in a 3.5 mm crystal length at an incident power intensity of about $100 \text{ MW}/\text{cm}^2$. The energy conversion efficiency of one KTP crystal (3.5-mm length) as a function of input power density is shown in Figure 8.

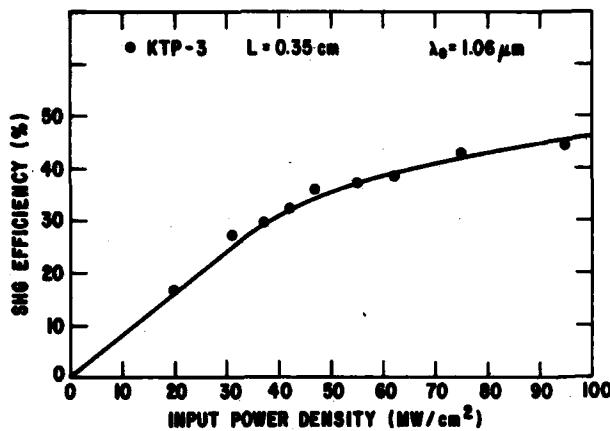


Figure 8. Conversion efficiency measured at a function of input power density at $1.06 \mu\text{m}$.

SUMMARY

The development of the high-power solid-state slab laser has greatly improved the beam brightness and average power capabilities obtainable from a solid-state laser. Previously, the average power from a solid-state laser has been limited by the thermal-optical distortion due to the relatively low thermal conductivity of the laser medium. In the slab-type solid-state laser, the optical beam inside the active medium undergoes total-internal reflection to provide a self-compensation of optical wavefront distortion due to thermally-induced index variation. Furthermore, because of the optical symmetry along a totally internally reflected zig-zag beam path, the net effect of the stress-induced birefringence disappears when integrated over the entire optical path inside the gain medium, and the depolarization effect is eliminated. This configuration makes possible a solid-state Nd:glass laser operable at a power level much exceeding that previously achieved, while maintaining a beam quality near the diffraction-limit. Nonlinear frequency conversion from a high-power slab-type solid-state laser offers the opportunity of developing high-

power visible laser sources exceeding 10 W average power level.

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